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Evaluation of Mechanical Ventilator Use with Liquid Oxygen Systems



Thomas Blakeman, MSc, RRT; Dario Rodriguez Jr., MSc, RRT; Richard Branson, MSc, RRT; John-Michael Fowler, BSN, RN; Matthew Worsham, RT; Nicole Alston, RT; Dina Gomaa, MSc, RRT; James Woods, MSc, RRT



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**Air Force Research Laboratory
711th Human Performance Wing
U.S. Air Force School of Aerospace Medicine
Aeromedical Research Department
2510 Fifth St., Bldg. 840
Wright-Patterson AFB, OH 45433-7913**

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COL NICOLE ARMITAGE
Chief, En Route Care Research Division

//SIGNATURE//

DR. RICHARD A. HERSACK
Chair, Aeromedical Research Department

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14. ABSTRACT Mechanical ventilators coupled with portable liquid oxygen (LOX) systems are critical components of the U.S. Air Force Critical Care Air Transport Team mission. Air Force Instruction 10-2909 recommends the number of ventilators that can safely be used with a single device, depending on the LOX device used. We evaluated two portable LOX systems with three different models of portable ventilators to determine the number of ventilators each device will accommodate at ground level and at simulated altitude. The PtLox and NPtLox liquid oxygen systems (Essex Industries, St. Louis, MO) and model 754 and 731 (Zoll Medical, Chelmsford, MA) and LTV® 1000 (Carefusion, San Diego, CA) ventilators were used for the evaluation. Lung conditions and ventilator settings represented a patient with acute respiratory distress syndrome and placed a high demand on the LOX. Testing was done at ground level and at simulated altitude of 8,000 feet in an altitude chamber. One ventilator was attached every minute until all oxygen connections were in use or until the LOX could no longer support the oxygen demand. At ground level and at altitude, the PtLox was able to accommodate the oxygen demand with the three available connections in use for all ventilator models. The NPtLox accommodated the oxygen demand using four ventilators with the 754, five to six with the 731, and three to four with the LTV 1000. The NPtLox was able to support an additional ventilator of each model at altitude. Current Air Force guidance recommends that a maximum of one ventilator be attached to the PtLox and two to the NPtLox. The number of ventilated patients determines how many LOX systems must be on the flight. The results of this study show that the number of ventilators that can be attached to each LOX can easily be doubled with no decline in ventilator performance.					
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1.0 SUMMARY

Mechanical ventilators coupled with portable liquid oxygen (LOX) systems are critical components of the U.S. Air Force Critical Care Air Transport Team mission. Air Force Instruction 10-2909 recommends the number of ventilators that can safely be used with a single device, depending on the LOX device used. We evaluated two portable LOX systems with three different models of portable ventilators to determine the number of ventilators each device will accommodate at ground level and at simulated altitude. The PtLox and NPtLox liquid oxygen systems (Essex Industries, St. Louis, MO) and model 754 and 731 (Zoll Medical, Chelmsford, MA) and LTV® 1000 (Carefusion, San Diego, CA) ventilators were used for the evaluation. Lung conditions and ventilator settings represented a patient with acute respiratory distress syndrome and placed a high demand on the LOX. Testing was done at ground level and at simulated altitude of 8,000 feet in an altitude chamber. One ventilator was attached every minute until all oxygen connections were in use or until the LOX could no longer support the oxygen demand. At ground level and at altitude, the PtLox was able to accommodate the oxygen demand with the three available connections in use for all ventilator models. The NPtLox accommodated the oxygen demand using four ventilators with the 754, five to six with the 731, and three to four with the LTV 1000. The NPtLox was able to support an additional ventilator of each model at altitude. Current Air Force guidance recommends that a maximum of one ventilator be attached to the PtLox and two to the NPtLox. The number of ventilated patients determines how many LOX systems must be on the flight. The results of this study show that the number of ventilators that can be attached to each LOX can easily be doubled with no decline in ventilator performance.

2.0 INTRODUCTION

In the current theater of operations, aeromedical evacuation of the critically ill/injured warrior poses numerous challenges. The use of mechanical ventilation in this setting is a well-established crucial component of the mission. Ensuring appropriate oxygen sources are available throughout the continuum of care is paramount to the success of these transports. Liquid oxygen (LOX) systems coupled with ventilators are used in most U.S. Air Force Critical Care Air Transport Team (CCATT) transports, yet the maximum performance of these systems is not well documented. We evaluated two LOX systems and three different models of portable ventilators that are available for CCATT transport use at sea level and simulated altitude.

3.0 METHODS

There are currently two LOX systems procured for CCATT use: PtLOX has a 10-liter liquid oxygen capacity and three connections for ventilators and NPtLOX has a 20-liter liquid oxygen capacity and six connections for ventilators. Both LOX systems are manufactured by Essex Industries, St. Louis, MO. Portable ventilators included in this evaluation were models 754 and 731 (Zoll Medical, Chelmsford, MA) and LTV® 1000 (BD/CareFusion, Franklin Lakes, NJ).

Test lung settings were a lung compliance of 20 mL/cm H₂O and resistance of 5 cm H₂O/L/s representing a patient with acute respiratory distress syndrome. A FlowAnalyzer™ PF-301 (IMT Medical, Buchs, Switzerland) was connected between the ventilator circuit and test

lung (TTL, Michigan Instruments, Grand Rapids, MI), and ventilator output of one ventilator, including flow, volume, pressure, and fraction of inspired oxygen (FIO₂), was recorded on a breath-to-breath basis for future analysis. This was done to determine if any degradation in tidal volume occurred when adding additional ventilators to the LOX devices. Ventilator settings were as follows: respiratory rate 35 breaths/min, inspiratory time 0.8 seconds, tidal volume 450 mL, positive end-expiratory pressure 20 cm H₂O, FIO₂ 100%. This combination of lung conditions and ventilator settings likely represents the extreme of ventilator and oxygen demands that may be encountered during aeromedical evacuation.

We had only one PtLOX available to use for the evaluation, so that device was used for every test. NPtLOX devices were chosen randomly to approximate real-world use encountered by CCATT. For each LOX system and each ventilator model, one ventilator was attached every minute until the maximum number of ventilators was attached to each LOX model (three for PtLOX and six for NPtLOX) or until the LOX system could no longer meet the demand of the next additional ventilator. A failure to meet the requirements of the connected ventilators was defined by the ventilator alarming insufficient gas source or degradation in delivered tidal volume or FIO₂ > 10% from set. The condition that created the failure was repeated three times to demonstrate acceptable reproducibility. After determining the maximum number of ventilators with the chosen ventilator model/LOX combination, the ventilators were operated for an additional 30 minutes, after which the same procedure was repeated with the remaining ventilator models. After the maximum number of ventilators was determined with the third ventilator model, the devices were operated until the volume of LOX decreased to 2 liters, as indicated by a digital gauge on the LOX system. The test was then terminated. An additional test was done with only the 731 ventilators operating on each LOX device until LOX volume again decreased to 2 liters. Each test was done two times, both at sea level and at simulated altitude of 8,000 feet, in an altitude chamber at Wright-Patterson Air Force Base, OH. Figure 1 shows the test setup with six ventilators attached to NPtLOX.



Figure 1. Test setup with six ventilators attached to NPtLOX.

4.0 RESULTS

The PtLOX was able to support the maximum number of ventilators for the number of outlet ports on which to connect (three). The number of ventilators that could be supported by the NPtLOX varied between ventilator models and NPtLOX devices and exposure to hypobaric conditions. Table 1 shows the maximum number of ventilators that could be supported by each LOX device at both test conditions.

Table 1. Maximum Number of Each Ventilator That the LOX Systems Could Support at Sea Level and 8,000 ft Altitude

Ventilator	PtLOX		NPtLOX	
	Sea Level	8,000 ft	Sea Level	8,000 ft
754	3	3	4	5-6
731	3	3	5-6	6
LTV 1200	3	3	3-4	4-5

5.0 DISCUSSION

Aeromedical evacuation is often accomplished utilizing aircraft of opportunity, configured to accommodate casualties. Portable LOX systems such as the PtLOX and NPtLOX are a necessity/option on aircraft not equipped with onboard oxygen. CCATT transports critically ill/injured patients who often require mechanical ventilators that utilize high-pressure oxygen to deliver higher oxygen concentrations. High-pressure oxygen must either come from pressurized oxygen cylinders or from LOX devices. During military contingencies, pressurized cylinders are not permitted on most aircraft due to the risk of explosion. Additionally, cylinders are logistically challenging due to their weight and cube and, for their size, provide a fraction of the oxygen volume that can be generated from LOX devices. For example, an H cylinder contains approximately 7,000 liters of gaseous oxygen but is nearly 5 feet tall and weighs approximately 110 pounds, is not considered portable, and must be moved using a specially designed cart. The NPtLOX contains 20 liters of liquid oxygen, which converts to 17,200 liters of oxygen gas, weighs 125 pounds when full, has a 3.8-ft² footprint [1], and is a two-person move requiring no special equipment to transport. The NPtLOX can accommodate up to six ventilators, whereas a pressurized cylinder can only accommodate one.

The ventilator settings used in the evaluation required an oxygen volume of 15.75 lpm to deliver the required minute ventilation. The LTV 1000 has a higher flow rate requirement for the same ventilator settings due to the device's use of a constant flow turbine and a bias flow during exhalation to facilitate triggering. The PtLOX could support the maximum number of ventilators (three) regardless of which ventilator model was used or if operated at ambient pressure or at altitude, despite exceeding the reported maximum flow rate of 15 lpm per oxygen outlet (45 lpm total maximum flow rate at 50 ± 5 psig) [2].

The study setup was the same when evaluating the NPtLOX, with the only difference being that there is a maximum of six oxygen outlets on which ventilators can be attached. Volume in lpm per oxygen outlet required to operate the ventilators was the same as with the PtLOX evaluation (15.75 lpm). The maximum number of ventilators that could be supported by the NPtLOX varied between ventilator models and exposure to hypobaric conditions. The

NPtLOX could support three to four LTV 1000 ventilators at ground level and four to five at altitude, four 754 ventilators at ground level and five to six at altitude, and five 731 ventilators at ground level and six at altitude.

The difference in the number of ventilators that could be supported by the NPtLOX is multifactorial. First, the stated maximum flow rate for the device is 11 lpm of continuous flow per oxygen outlet (66 lpm total flow using six outlets) while maintaining device pressure of 50 ± 5 psig [2]. During this evaluation, lpm used by the ventilators was often greater than the stated maximum total flow of 66 lpm. There are two possible reasons why the NPtLOX was able to meet the demands of multiple devices. The ventilators can operate at pressures less than 50 psig without degradation in delivered tidal volume. The LTV 1000 and 754 can operate down to a pressure of 35 psig and the 731 can operate down to 31 psig. Once the NPtLOX pressure drops below these thresholds, the ventilators will sound a low pressure alarm but will continue to deliver the selected tidal volume via room air generated by the ventilators' internal compressor. This, however, results in a fall in the delivered FIO₂. Another explanation for the perceived higher output may be that although the stated limitation is 66 lpm, this is continuous flow and the device may have a much higher instantaneous flow output. The greatest demand placed on the NPtLOX was during tidal volume delivery. In our evaluation, for each breath the tidal volume was delivered in 0.8 seconds, leaving 0.9 seconds for the expiratory phase, at which time there is no demand on the LOX system. Ventilators deliver intermittent flow compared to the constant output of the LOX. This allows the LOX system to meet high intermittent demand greater than the stated outflow.

When evaluating the NPtLOX at altitude, with each ventilator model, the maximum number that could be simultaneously operated increased by 1. The most likely reason for the increased performance is due to Boyle's law, which states that at a constant temperature, pressure and volume are inversely related. Therefore, gas expansion may account for the ability of the NPtLOX to support more ventilators at altitude as compared to ground level. Additionally, at altitude, the NPtLOX used less oxygen than at ambient pressure and therefore lasted longer using the same number of ventilators with no degradation in tidal volume. For example, when operating the NPtLOX with six 731 ventilators at altitude, oxygen use was 5.2 liquid liters per hour. At ground level, liquid oxygen use was 6.8 liquid liters per hour. Liquid oxygen volumes were displayed on the NPtLOX and recorded every 30 minutes during each evaluation.

Current Air Force aeromedical transport guidance limits the number of ventilators that can be attached to a LOX device to one for the PtLOX and two for the NPtLOX. One CCATT can transport up to three mechanically ventilated patients simultaneously. Under the current guidance, three PtLOX or two NPtLOX must be utilized to provide a high-pressure oxygen source for the three ventilated patients. The results of this study demonstrate the potential to generate resource efficiencies while maintaining the appropriate support for mechanically ventilated casualties. However, a reduction in the number of oxygen sources should be met with careful consideration due to LOX off-gassing to the atmosphere of approximately 1 liquid liter per day due to evaporation. Accurate calculation of oxygen requirements is paramount to mission success.

An extensive search of the medical literature did not reveal any manuscripts relevant to aeromedical transport and concurrent use of LOX for patient care. The focus of the majority of the literature was the use of LOX in the home for patients receiving chronic oxygen therapy [3-8] and frostbite injuries sustained during LOX handling [9,10].

6.0 CONCLUSIONS

Oxygen supplies are a critical asset when transporting critically ill/injured patients. Some fixed wing and rotary wing aircraft do not have onboard oxygen for use by care teams. Liquid oxygen provides a safe alternative to pressurized cylinders that minimizes weight and cube inside the aircraft and provides a large amount of oxygen, which are important logistical planning factors. Critically ill, mechanically ventilated patients often require high levels of oxygen, which can put a strain on oxygen resources. Current Air Force guidance is to use a maximum of one ventilator per PtLOX and two for NPtLOX, which often necessitates having multiple LOX devices onboard the aircraft if there are multiple ventilated patients to comply with the guidance. The results of this study showed that the maximum number of ventilators used on both LOX devices, at a minimum, can be doubled without a decline in performance of the LOX or the ventilators. This could provide a logistics advantage by freeing up floor space in an already crowded environment and provide a financial benefit by not filling LOX devices needlessly.

7.0 LIMITATIONS

The main limitation of this study is that it was a bench model in a well-controlled environment. We assume that under the same conditions during an actual mission, the results would be similar. We used ventilator settings that may be used with patients who have acute respiratory distress syndrome requiring 100% oxygen. It is possible, although unlikely, that CCATT would transport patients with that high of an oxygen requirement. We used 100% oxygen in this study to simulate the maximum requirement of oxygen from the LOX devices, therefore discovering the maximum capabilities. A more likely scenario during an actual CCATT transport would be a lower ventilator respiratory rate and oxygen settings of $\leq 50\%$. Mathematically, a 50% reduction in oxygen requirement may allow the LOX devices to operate the maximum number of ventilators that can be attached, although we did not evaluate this scenario in our study.

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LIST OF ABBREVIATIONS AND ACRONYMS

CCATT Critical Care Air Transport Team

FIO₂ fraction of inspired oxygen

LOX liquid oxygen